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Beacon Beams for Deep Turbulence High Energy Laser Beam Directors

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14. ABSTRACT

The objective of this report is to outline a new type of beam director for deep turbulence propagation of high energy lasers (HELs). The proposed beam director is based on a new and innovative approach employing a Brillouin enhanced four-wave mixing mechanism for generating a tight (small spot size) beacon beam on a remote target. This mechanism results in amplification and complete conjugation (phase and amplitude) of the beacon beam without the need for wavefront sensors, deformable mirrors or predictive feedback algorithms. Complete phase conjugation is critical for beam control in the presence of strong turbulence. Conventional AO techniques do not have this capability. The beacon beam phase information from the beacon beam can be used in conjunction with an AO system to propagate HEL beams in deep turbulence.

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Beacon Beams for Deep Turbulence High Energy
Laser Beam Directors

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Abstract

The objective of this report is to outline a new type of beam director for deep turbulence propagation of high energy lasers (HELs). The proposed beam director is based on a new and innovative approach employing a Brillouin enhanced four-wave mixing mechanism for generating a tight (small spot size) beacon beam on a remote target. This mechanism results in amplification and complete conjugation (phase and amplitude) of the beacon beam without the need for wavefront sensors, deformable mirrors or predictive feedback algorithms. Complete phase conjugation is critical for beam control in the presence of strong turbulence. Conventional AO techniques do not have this capability. The phase information from the beacon beam can be used in conjunction with an AO system to propagate HEL beams in deep turbulence.

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I.   Introduction

Effective beam control of high energy lasers (HELs) is a key component of a laser weapon system. Strong (deep) turbulence can have a significant deleterious effect on the propagation of the HEL beam [1,2]. Deep turbulence is characterized by a Rytov number (log-amplitude variance) of $\sigma_\chi^2 > 0.25$. The Rytov variance (log-intensity) is given by $\sigma_R^2 = \exp(4\sigma_\chi^2) - 1$, which is approximately equal to $4\sigma_\chi^2$ for $\sigma_\chi^2 << 0.5$. Expressed in terms of the atmospheric refractive index structure constant C_n^2, wavelength λ and propagation length L_T the Rytov variance $\sigma_R^2 \approx 4\sigma_\chi^2 = 10.5 C_n^2 \lambda^{-7/6} L_T^{11/6}$. The amplitude and phase information from a beacon beam records the turbulence and target surface irregularities. Propagation of the beacon beam in deep turbulence results in large intensity scintillations on the target and, in a conventional beam director, on the AO wavefront sensors [3]. The intensity scintillations are characterized by an intensity variance σ_I^2 that can be expressed in terms of the Rytov variance: $\sigma_I^2 \approx \sigma_R^2$ for $\sigma_R^2 < 0.5$ and $\sigma_I^2 \approx 1 + (\sigma_R^2)^{-2/5}$ for $\sigma_R^2 >> 1$ [4]. To minimize the effects of turbulence a tight beacon beam on target is necessary. These fluctuations lead to intensity nulls and branch points, which can result in uncertainty in the phase. The discontinuities in the wavefront cannot be measured using conventional wavefront sensors, e.g., Shack-Hartman sensors.

Here we outline an amplified optical phase conjugation (OPC) approach for beacon beam formation that fully conjugates the field [5]. Complete field conjugation is accomplished by employing a Brillouin enhanced four-wave mixing mechanism (BEFWM). By using this approach a tight beacon beam can be formed on the target. Using wavefront sensors the phase and amplitude information is then relayed to the deformable mirror directing the HEL beam to the target.

II.   Beacon Beam Formation

We propose to form a beacon beam using a four-wave nonlinear optical phase conjugation mechanism. Optical phase conjugation based on four wave mixing is a well developed technique for correcting optical aberrations in laser cavities [6-11]. We use a

variation of this optical conjugation technique, together with spatial filtering (aperturing) in the conjugate image plane, to form a tight beacon beam on a remote target [12].

Advantages of this approach include: i) high spatial and temporal resolution of the conjugated field and ii) high amplification of the conjugated field, i.e., improved signal-to-noise ratio. Figure 1 is a schematic of the beam director using a Cassegrain reflector. Nonlinear mixing of the optical beams (pump and beacon) takes place in the nonlinear medium, i.e., carbon disulphide (CS_2). The amplified OPC can provide the phase and amplitude information, related to the turbulence and target surface, to the AO system (deformable mirrors) for the HEL.

The target is initially fully illuminated by a large spot size beacon beam. A spatial filter (aperture) is placed in the conjugate image plane associated with the illuminated target and a small spot on the target is selected forming a tight beacon beam. The beam, from the small spot on the target, is conjugated and sent back to target. This process is repeated until a satisfactory, small spot size beacon beam is generated, typically requiring < 10 round trips. The time required to form a tight beacon beam is short compared to the time scale for atmospheric change, i.e., inverse of the Greenwood frequency.

Figure 2 is a schematic of the amplified OPC configuration. The phase conjugator contains CS_2, with Brillouin frequency Ω, as the nonlinear medium where the four waves are combined resulting in Brillouin enhanced four wave mixing. The nonlinear polarization is due to the electrostriction process and results in the formation of the conjugated beacon beam. This approach is equivalent to recording a volume hologram in real time in the nonlinear medium and then reading the hologram to reconstruct the field and generating the conjugated field. In order for the incoming and conjugated outgoing beacon beams to have the same frequency, $\omega = \omega_1 - \Omega$, the two pump beams must have a frequency difference equal to twice the Brillouin frequency shift, Ω. To accomplish this, the primary pump, E_1 with frequency ω_1 is Brillouin backscattered in a temperature controlled cell containing glycerol (with Brillouin frequency 2Ω) producing the second pump E_2 at frequency $\omega_1 - 2\Omega$. In this approach the pump beams are conjugates of each other which is highly desirable for the amplified OPC process. In the limit of negligible wave-vector mismatch the conjugated beacon beam intensity gain is given by the ratio of the pump intensities, i.e., $G = I_1 / I_2 = |E_1|^2 / |E_2|^2$, which can be as high as $\sim 10^3$. The high gain regime implies that $g_o I_1 L_{CS_2} >> 1$, where $g_o = 0.075 \, \text{cm/MW}$ is the line center amplitude gain,

3

$I_1[\mathrm{MW/cm}^2]$ is the pump intensity, and $L_{CS_2}[\mathrm{cm}]$ is the length of the CS_2 interaction. For $L_{CS_2} = 10\,\mathrm{cm}$, the required pump intensity is $I_1 \geq 10\,\mathrm{MW/cm}^2$. The spectral line width of the phase conjugation mechanism is $\Delta\Omega/\omega \approx 5\times10^{-7}$, which is sufficiently broad for the beacon beam. An example of the pulse format of the beacon beam in the ring resonator configuration is shown in Fig.3. The illustrative beacon beam/pump parameters are listed in Table I.

Figure 4 shows the propagation of the rays between the optical phase conjugator and the target. The rays representing the beacon beam propagate back and forth through the lens and the spatial filter. The location of the conjugate image plane, with respect to the lens, is $L_I = L_F/(1 - L_F/L_T) \approx L_F$, where L_F is the focal length of the lens and L_T is the target range. The target spot size in the image plane (in the geometric optics limit and in the absence of turbulence) is $R_I = R_T\,L_I/L_T$ where R_T is the target radius. The diffraction limited spot size (for $L_T \to \infty$) in the image plane, is $R_{\min} \approx \lambda_1 L_F/(\pi R_L)$ where R_L is the radius of the lens. As an example, for $\lambda_1 = 1\,\mu\mathrm{m}$, $L_F = 2\,\mathrm{m}$, $L_T = 2\,\mathrm{km}$, $R_T = 30\,\mathrm{cm}$ and $R_L = 3\,\mathrm{cm}$, the spot size of the target in the image plane is $R_I = 0.3\,\mathrm{mm}$ while the diffraction limited spot size is $R_{\min} \approx 20\,\mu\mathrm{m}$.

By spatially filtering the image of the target by a factor of $\alpha_A = R_A/R_I < 1$ where R_A is the radius of the aperture (spatial filter), and fully conjugating the field, we find, in the presence of turbulence, that the radius of the returned (focused) beacon beam on target is $\tilde{R}_T \approx ((\alpha_A R_I/L_I)^2 + (1.7\lambda_1/\pi r_o)^2)^{1/2} L_T$. The transverse coherence length (Fried parameter) is $r_o = 0.184(\lambda_1^2/(C_n^2 L_T))^{3/5} = 0.75(\lambda_1 L_T)^{1/2} \sigma_R^{-6/5}$ where $\sigma_R^2 = 4\sigma_\chi^2 = 10.5\,C_n^2\,\lambda_1^{-7/6}\,L_T^{11/6}$ is the Rytov variance and C_n^2 is the atmospheric refractive index structure constant. The effect of turbulence on the focused beacon beam on target, $\tilde{R}_T$, becomes important when $r_o \leq 1.7\lambda_1 L_T/(\pi\alpha_A R_T) \sim 1\,\mathrm{cm}$.

The fraction of the beacon beam photons f_{BB} returned from the diffuse target scales like $D^2 \eta_T/L_T^2$, for receiver aperture diameter $D = 0.5\,\mathrm{m}$, target reflectivity $\eta_T \approx 0.1$, and a target range of $L_T = 2\,\mathrm{km}$ is $f_{BB} \approx 10^{-8}$. For a $E_{BB} = 1\,\mathrm{J}$ beacon forming beam pulse the returned beacon beam energy is $\sim 10^{-8}\,\mathrm{J}$ ($\sim 5\times10^{10}$ photons). Table II lists the beacon beam/target parameters.

III.   Numerical Example

The atmospheric propagation code HELCAP was used to simulate the proposed concept in a simplified configuration in order to demonstrate the capabilities for full-scale simulations of a realistic turbulent propagation path. A collimated Gaussian pulse with a spot size of 10 cm and a wavelength of 1 µm was propagated to a target with a radius of 10 cm at a range of 1 km through a turbulent environment characterized by Rytov variance $\sigma_R^2 = 2$ ($\sigma_\chi^2 \approx 0.5$) and Fried parameter $r_o \sim 1$cm   The beam was reflected from the target back to the imager where it passes through a long focal length lens. The beam then passes through a 1 mm radius aperture in the image plane before being fully conjugated and sent back through the lens to the target. In the absence of turbulence this illuminates the target with a 1 cm spot size beam, i.e., a factor of 10 reduction from the initial beam. Figure 5 plots the spot size on the target before passing through the conjugating illuminator (panel a) and after one pass (panel b). The spot size on target is 10 cm before passing through the imager and 3.7 cm after one pass through the imager while the FWHM of the beacon beam intensity on target is ~1 cm.

IV.   Conclusions

In this report we have outlined a novel approach to beacon beam formation for high energy laser beam propagation in deep turbulence. In this approach complete phase conjugation of the beacon beam is accomplished by employing Brillouin enhanced optical four wave mixing. A beacon beam formed by this approach has a number of significant characteristics:

> i) complete wavefront conjugation (amplitude and phase)
> ii) branch points on the target-returned field are not an issue
> iii) conjugated beam has high gain ($\sim 10^3$)
> iii) wavefront sensors are not required for beacon beam formation
> iv) amplified OPC medium has fast temporal response ($\sim$ nsec) and high
>   spatial resolution (< 1 µm)
> v) tight beacon beam formation converges rapidly (< 10 round trips)

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Spot size of pump laser, R_o	1 mm
Intensity (pump 1), I_1	10 MW/cm^2
Intensity (pump 2), I_2	10 kW/cm^2
Pump-beacon beam angular separation, θ	2°
Beacon beam gain, $G = I_1 / I_2$	10^3
Length of CS$_2$ cell, L_{CS_2}	10 cm
Length of SBS (glycerol) cell, L_{SBS}	10 cm

Table I. Pump and beacon beam parameters.

Target range, L_T	2 km
Beacon beam pulse length, τ_{BB}	10 nsec
Beacon beam pulse energy, E_{BB}	1 J
Receiver aperture, D	50 cm
Target reflectivity, η_T	0.1
Fraction of beacon beam returned, f_{BB}	10^{-8}
Beacon beam spot size (on phase conjugate mirror)	0.3 mm
Beacon beam (target returned) amplification factor	10^2
Beacon beam intensity (on phase conjugate mirror), I_{BB}	74 kW/cm^2
Beacon beam (outgoing) amplification factor	10^3

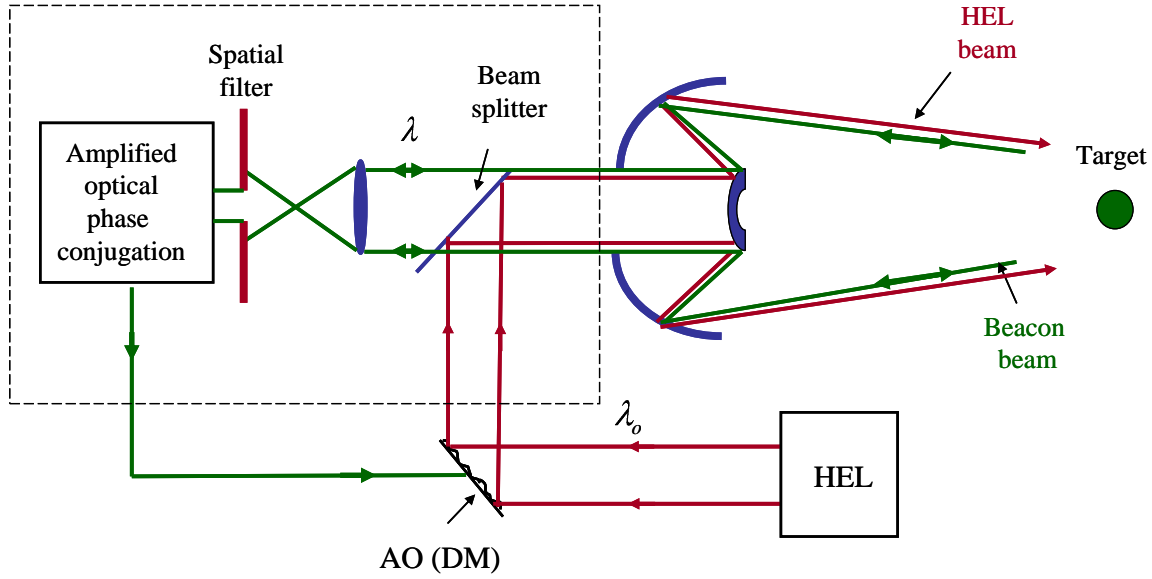Table II. Target and beacon beam parameters.

Figure 1: Schematic of overall beam director employing an amplified Optical Phase Conjugator (OPC) with a Cassegrain reflector for propagation of beacon/HEL beams in deep turbulence. The beacon beam, formed by a four-wave mixing process, interrogates the target surface and the turbulence along the propagation path. The amplitude and phase information on the beacon beam is used in conjunction with an AO system (deformable mirror, DM) to propagate the HEL beam. The dashed area encloses the beacon beam/phase conjugation part of the beam director.
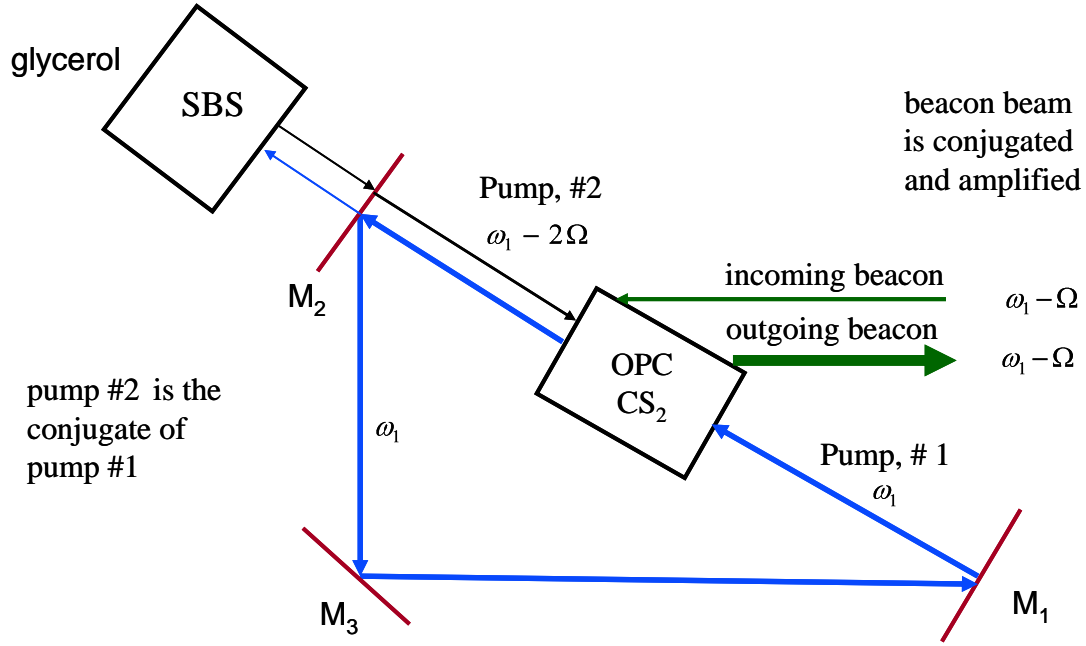
Figure 2: Schematic details of the beacon beam formation by a Brillouin-enhanced four-wave mixing process. The box labeled amplified OPC contains a nonlinear medium, e.g., CS_2, in which four-wave mixing takes place. Two of the waves are the incoming beacon beam E_3 at frequency $\omega_1 - \Omega$ and the amplified beacon beam E_4 at the same frequency. The other waves are a pump wave E_1 at frequency ω_1 and the stimulated backscattered pump wave E_2 at frequency $\omega_1 - 2\Omega$, where Ω is the Brillouin frequency shift of the nonlinear medium, e.g., glycerol, in the box labeled SBS.
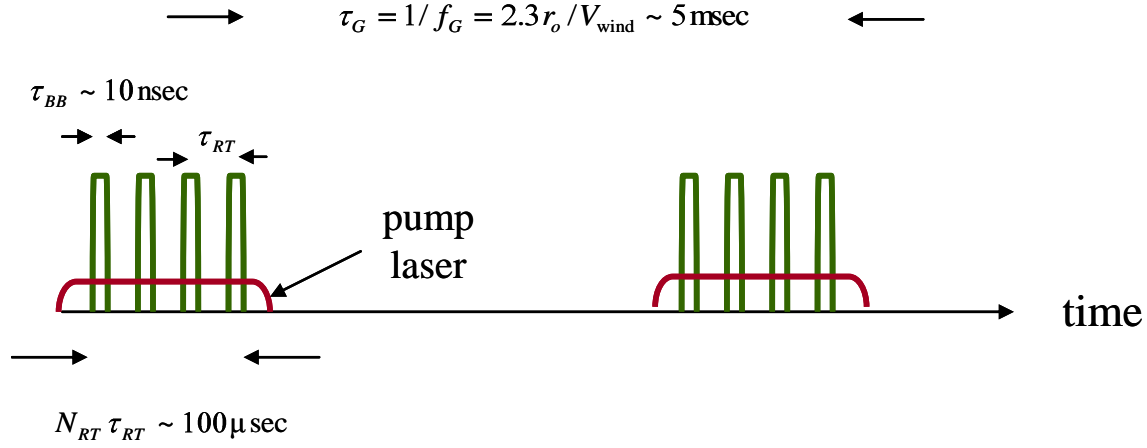
$$\tau_G = 1/f_G = 2.3\,r_o/V_{\text{wind}} \sim 5\,\text{msec}$$

$\tau_{BB} \sim 10\,\text{nsec}$

τ_{RT}

pump
laser

time

$N_{RT}\,\tau_{RT} \sim 100\,\mu\,\text{sec}$

Figure 3: Pulse format of the beacon beam.

Spatial
Filter
(image plane)

Illuminated
target

R_L

R_I

R_A

OPC

Small
spot size
beacon
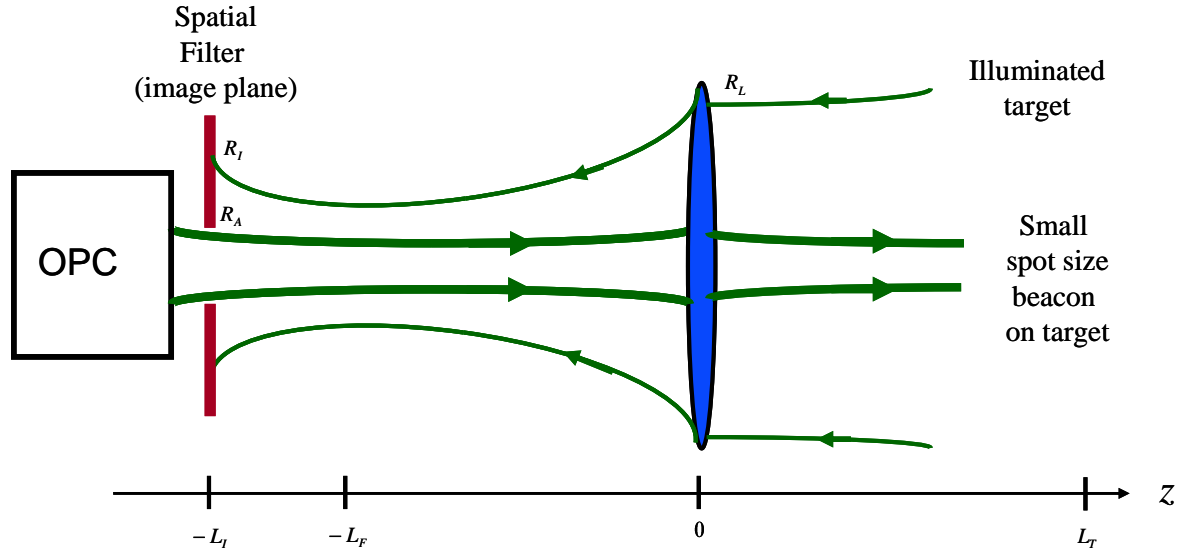on target

$-L_I$ $-L_F$ 0 L_T z

Figure 4: Diagram illustrating ray propagation between the amplified optical phase conjugator (AOPC) and target through the lens. A spatial filter of radius R_A is positioned in the conjugate (image) plane of the lens. This allows a tight beacon beam to be formed on the target.
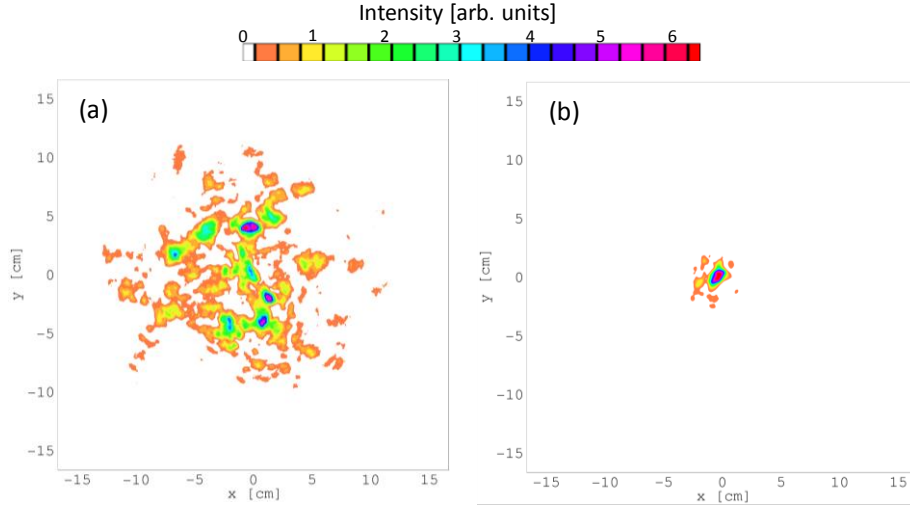
Figure 5: Intensity profiles of a beacon beam on the target after one pass. An intensity gain factor of 8 is assumed in the phase conjugating cell and Rytov variance $\sigma_R^2 = 2$. In the absence of turbulence, the illuminator system produces a spot size of 1 cm on the target.